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研究課題名（和文）Development of Ultimate Low-Noise Magnetic Field Sensors Using Novel Sensing Layer in Magnetic Tunnel Junctions for Sensing-Driven Society

研究課題名（英文）Development of Ultimate Low-Noise Magnetic Field Sensors Using Novel Sensing Layer in Magnetic Tunnel Junctions for Sensing-Driven Society

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研究成果の概要（和文）：磁気トンネル接合（MTJ）センサのノイズの一つのマイクロ的な起源を調べた。磁壁の位置揺らぎにより可視化処理で明らかにした。そのノイズ低減更にセンサ自由層の設計と材料が複数の種類を開発した。センサ磁壁固定と、動作温度向上と、渦磁化状態（ボルテックス）のセンサの成果を得られた。更に、低ダンピングの磁性酸化物薄膜の作成が成功した。

研究成果の学術的意義や社会的意義
We clarified an origin of magnetic noise in magnetic tunnel junction sensors, and developed new sensing devices and materials. This advances understanding of magnetic fluctuations in micro-sized sensors, and adds to applications in cheap low-power sensors, such as IoT and biomedical fields.

研究成果の概要（英文）：The spintronic sensors based on magnetic tunnel junctions (MTJs) are promising in the domains of Internet-of-Things (IoT), automotive, biomedical, etc. A main obstacle is the intrinsic magnetic noise processes. In this research, we investigated the origin of noise in MTJ sensors, and we designed new thin-film sensing layers. First, we clarified the microscopic origins of magnetic noise using magnetic domain imaging. We found that the magnetic domain wall fluctuations are a major contribution to low-frequency noise. Secondly, we investigated new sensing layers of: (a) permalloy/platinum manganese exchange-coupled layers, (b) vortex formation in circular sensing devices, and the control of sensitivity in the vortex-type MTJs, and (c) yttrium iron garnet thin films.

研究分野：Spintronics

キーワード：spintronics　sensors　YIG　PtMn　Vortex

１．研究開始当初の背景

Hall sensors have dominated the magnetic sensor applications. Stringent requirements of high sensitivity, high linearity, low power consumption, and low noise are required for the emerging applications in in automotive, internet-of-things (IoT), and biomedical fields. The spintronic sensors based on magnetic tunnel junctions (MTJs) are gaining an increased use. A main obstacle is the intrinsic magnetic noise processes, where they hinder the detection of low-frequency (<10 Hz) signals. An understanding of the microscopic origin of the magnetic nosie, and finding new methods to overcome it are highly needed.

２．研究の目的

Recently, MTJs have been demonstrated in measuring heart and brain magnetic fields [Fujiwara *et al*., Appl. Phys. Express 11 , 023001 (2018)]. However, the MTJ sensors are still limited by the magnetic domain noise, which deteriorates the signal-to-noise ratio (SNR). Therefore, we ① investigate a microscopic analysis of magnetic noise origin, and ② develop new types of sensing layers in MTJ sensors.

３．研究の方法

① We analyzed the microscopic origins of magnetic noise using magnetic domain images. We developed magneto-optical Kerr effect (MOKE) microscope with a low-noise scientific CMOS camera and a stabilized light source. We explored the time evolution and spectral density of fluctuations in micro-sized permalloy islands at low magnetic fields.

② We developed three new sensing layers (2-a,b,c): (a) permalloy/platinum manganese exchange-coupled layers, (b) vortex formation in circular sensing devices, and the control of sensitivity in the vortex-type MTJs, and (c) yttrium iron garnet thin films.

We used ultra-high-vacuum sputtering for multilayer film growth. To measure the films' atomic composition, we used an inductively-coupled plasma mass spectrometer. For magnetic characterization, we used vibrating sample magnetometer (VSM) and cavity-mode ferromagnetic resonance (FMR) spectrometer. For sensor devices, we prepared MTJ stacks of (sensor layer/MgO/pinned layer), then we fabricated devices using photolithography, electron-beam lithography, and Ar ion milling.

a　We optimized the growth and exchange-bias in $L1_0$-PtMn antiferromagnet. We made an exchange-coupled PtMn/NiFe sensing layer, and investigated the domain structure by MOKE domain imaging. Furthermore, we used MTJ sensors that operate at high temperatures (>250℃).

b　We developed vortex-type MTJ sensors. We used electron-beam lithography to control the design of the vortex sensing layer, and the size of pinned layer, and to obtain a perfect alignment during microfabrication process.

c　We optimized stoichiometric high-quality $Y_3Fe_5O_{12}$ (YIG) films on Si and $Gd_3Ga_5O_{12}$ substrates. We varied the deposition parameters of deposition power, working pressure, and oxygen/argon gas stoichiometery. We optimized for low surface roughness, high saturation magnetization

(M_s), and low FMR damping constant.

４．研究成果

① The main results of this research are the new sensing layers that can decrease the sensor noise.
In the investigation by MOKE imaging [Fig. 1], we found that magnetic multi-domain states form at low applied fields. We measured power spectral density (PSD) at multi-domain and single-domain states from a 1-hour-long time-series of images. We found a substantial increase of low-frequency noise power in the multi-domain state [Fig. 1].

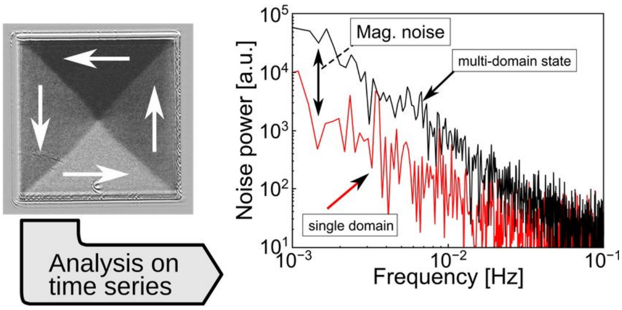

Fig. 1: The PSD analysis of magnetic domain fluctuations. The side length of the square NiFe island is 80 μm.

The magnetic magnetic random telegraphic noise (RTN) comes from domain-walls abruptly jumping between pinning sites, resulting in unstable fluctuations between discrete states, and a 1/*f* noise character. Due to these reasons, the total magnetic noise increases at the important sensing region near zero-field.

Increasing sensor total area is usually a simple solution to decrease noise power, but the ferromagnetic sensing layer breaks into a multi-domain state, and noise at domain walls increases. Decreasing 1/*f* noise is at a dilemma between the need for a large magnetic volume, and the multi-domain RTN. A fundamental solution is much needed.

②-a We showed that using exchange bias (EB) stabilizes domain walls in NiFe islands [1]. We optimized the growth of $L1_0$-PtMn antiferromagnetic layer, and the EB in PtMn/NiFe soft-magnetic sensing layer. The domain walls stabilize along the EB pinning direction [Fig. 2].

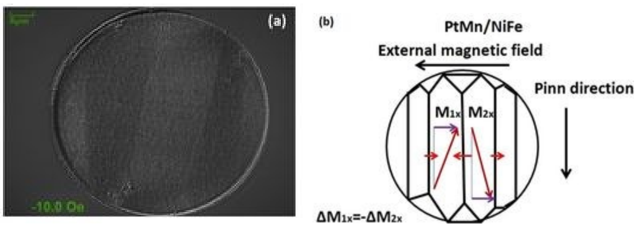

Fig. 2: Stabilizing domain walls by exchange bias. From results of [1].

Furthermore, we showed that EB from $L1_0$-PtMn is stable even at very high temperatures, and we made a magnetic sensor that operates at >250℃ [2]. Such a range opens the way for magnetic sensing in many applications of extereme environments, such as chemical plants, engines, and nano-satellites.

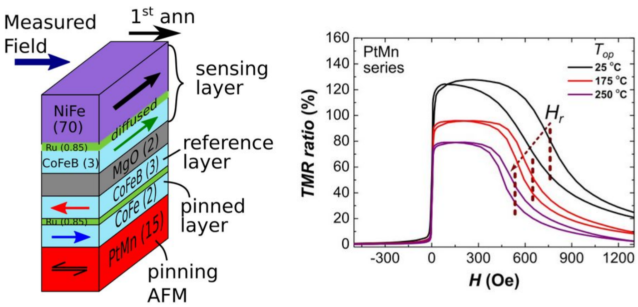

Fig. 3: High-temperature magnetometer using PtMn EB layer. From results of [2].

②**-b** The magnetic vortex configuration is topologically-protected, thus is has potential for low-noise sensors [Suess *et al.*, *Nature Electronics* 1, 362 (2018)]. However, the sensitivity is defined by the magnetostatic boundary conditions, and the sensitivity cannot be increased significantly. We showed in [3] that the control of pinned layer size can enhance sensitivity, independent from the vortex sensing layer. We devoloped the MTJ sensor and microfabrication process of Figs. 4(a,b), using multiple steps of electron-beam lithography and Ar ion milling. We controlled the vortex layer and the pinned layer radii (R_b, r_t). In the sensor transfer curves of Fig. 4(c), we showed the increase of sensitivity by decreasing r_t . We obtained a high sensitivity of up to 4.4 %/Oe for our smallest r_t = 1μm.

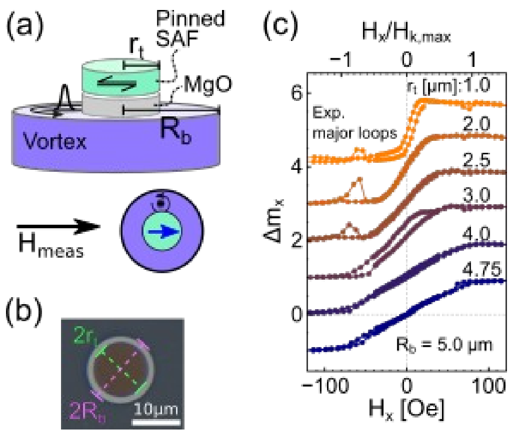

Fig. 4: (a) A schematic of vortex-type MTJ sensor. (b) A micrograph of a fabricated device. (c) Control of sensor sensitivity by pinned layer size. From results of [3].

②**-c** Gilbert damping constant (α_G) increases the magnetic noise [Egelhoff *et al*., *Sensors and Actuators A* 155 , 217 (2009)]. YIG has the lowest damping among know materials ($\alpha_G \sim 10^{-5}$ in bulk form). We fabricated YIG thin films on different substrates and underlayers. We investigated the sputter deposition parameters of deposition power, working pressure, oxygen/argon gas composition, and post annealing

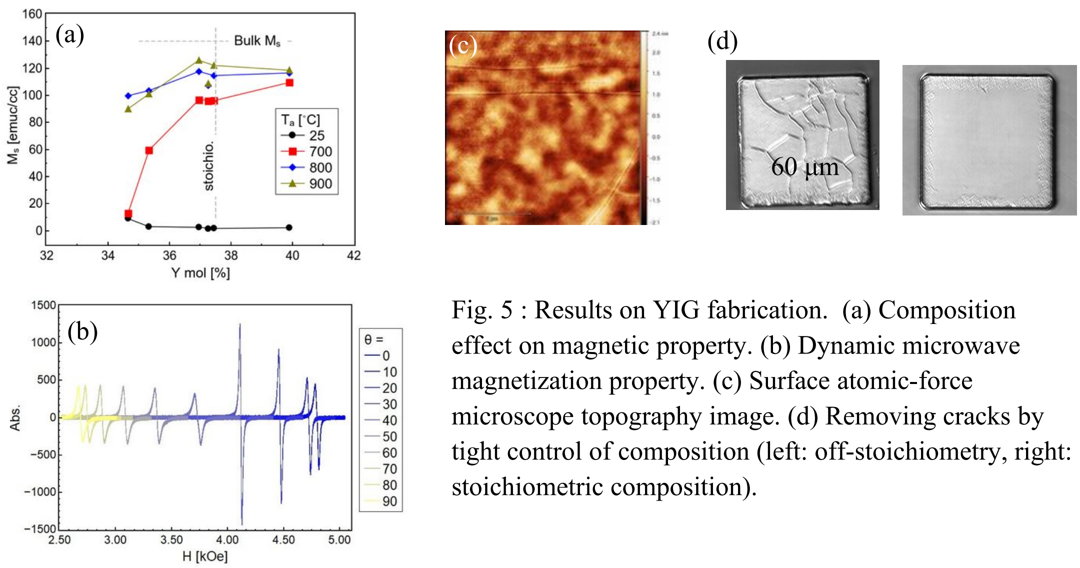

Fig. 5 : Results on YIG fabrication. (a) Composition effect on magnetic property. (b) Dynamic microwave magnetization property. (c) Surface atomic-force microscope topography image. (d) Removing cracks by tight control of composition (left: off-stoichiometry, right: stoichiometric composition).

temperature. We show that YIG thin films fabrication requires tight control of Y:Fe ratio within <1% of the stoichiometric ratio. We obtained high saturation magnetization close to bulk value [Fig. 5(a)], and very narrow linewidth FMR spectra of 10 Oe [Fig. 5(b)]. Using atomic-force microscope scanning, we demonstrated that our samples have flat surface with low surface roughness Ra < 0.4 nm [Fig. 5(c)]. A main obstacle in applications of YIG is the large thermal mismatch between YIG films and Si substrates, and the formation of cracks.With our method of composition control, we demostrate that stoichiometric

YIG devices form flat surface without cracks,whereas off-stoichiometric YIG films have a large crack density [Fig. 5(d)].

Research summary:

We developed better understanding of microscopic origin of free layer noise in MTJ sensors, and we developed various new sensing layers that expand into high-temperature opearation, topologically-protected vortex configurations, and low-damping YIG devices.

Furthermore, we also used this research results to expand into: developing new deep-learning algorithms for noise processing, and investigating spin-caloric effects in YIG/PtMn thin films.

These research results paves the way for future developments in magnetic sensing technologies.

[1] S. Ranjbar, M. Al-Mahdawi, M. Oogane, and Y. Ando, "Controlling domain configuration of the sensing layer for magnetic tunneling junctions by using exchange bias," *AIP Advances*, vol. 10, no. 2, p. 025119, Feb. 2020.

[2] S. Ranjbar, M. Al-Mahdawi, M. Oogane, and Y. Ando, "High-Temperature Magnetic Tunnel Junction Magnetometers Based on $L1_0$-PtMn Pinned Layer," *IEEE Sensors Letters*, vol. 4, no. 5, p. 2500504, Apr. 2020.

[3] M. Endo, M. Al-Mahdawi, M. Oogane, and Y. Ando, "Control of sensitivity in vortex-type magnetic tunnel junction sensors by the pinned layer geometry," (*submitted to Applied Physics Express*).

５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　3件／うち国際共著　3件／うちオープンアクセス　1件）

１．著者名 Ranjbar Sina、Al-Mahdawi Muftah、Oogane Mikihiko、Ando Yasuo	４．巻 10
２．論文標題 Controlling domain configuration of the sensing layer for magnetic tunneling junctions by using exchange bias	５．発行年 2020年
３．雑誌名 AIP Advances	６．最初と最後の頁 025119～025119
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/1.5130486	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Mohsen Attayeb、Al-Mahdawi Muftah、Fouda Mostafa M.、Oogane Mikihiko、Ando Yasuo、Fadlullah Zubair Md	４．巻 －
２．論文標題 AI Aided Noise Processing of Spintronic Based IoT Sensor for Magnetocardiography Application	５．発行年 2020年
３．雑誌名 Proceedings of ICC 2020 - 2020 IEEE International Conference on Communications	６．最初と最後の頁 1～6
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/ICC40277.2020.9148617	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Ranjbar Sina、Al-Mahdawi Muftah、Oogane Mikihiko、Ando Yasuo	４．巻 4
２．論文標題 High-Temperature Magnetic Tunnel Junction Magnetometers Based on L1$_0$-PtMn Pinned Layer	５．発行年 2020年
３．雑誌名 IEEE Sensors Letters	６．最初と最後の頁 1～4
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/LSENS.2020.2991654	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計7件（うち招待講演　1件／うち国際学会　7件）

１．発表者名 Ranjbar Sina、Al-Mahdawi Muftah、Oogane Mikihiko、Ando Yasuo
２．発表標題 Controlling domain configuration for the sensing layer of magnetic tunneling junction by using exchange bias
３．学会等名 64th Annual Conference on Magnetism and Magnetic Materials（国際学会）
４．発表年 2019年

1．発表者名
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2．発表標題
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3．学会等名
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4．発表年
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1．発表者名
Al-Mahdawi Muftah

2．発表標題
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4．発表年
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1．発表者名
Al-Mahdawi Muftah

2．発表標題
Potential of Spintronic Sensors in Healthcare IoT

3．学会等名
IEEE World Forum on Internet of Things（国際学会）

4．発表年
2020年

1．発表者名
Mohsen Attayeb、Al-Mahdawi Muftah、Fouda Mostafa M.、Oogane Mikihiko、Ando Yasuo、Fadlullah Zubair Md

2．発表標題
AI Aided Noise Processing of Spintronic Based IoT Sensor for Magnetocardiography Application

3．学会等名
ICC 2020 - 2020 IEEE International Conference on Communications（国際学会）

4．発表年
2020年

１．発表者名 Sakib Sadman、Fouda Mostafa M.、Al-Mahdawi Muftah、Mohsen Attayeb、Oogane Mikihiko、Ando Yasuo、Fadlullah Zubair Md
２．発表標題 Noise-Removal from Spectrally-Similar Signals Using Reservoir Computing for MCG Monitoring
３．学会等名 ICC 2021 - 2021 IEEE International Conference on Communications（国際学会）
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１．発表者名 Ranbar Sina、Yagmur Ahmet、Al-Mahdawi Muftah、Oogane Mikihiko、Ando Yasuo、Tanabe Kenshi、Awano Hiroyuki
２．発表標題 Spin Seebeck Effect in Antiferromagnetic PtMn/YIG(Yttrium Iron Garnet) Thin Films
３．学会等名 IEEE International Magnetics Conference (Intermag)（国際学会）
４．発表年 2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

Under review: M. Endo, M. Al-Mahdawi, M. Oogane, and Y. Ando, “Control of sensitivity in vortex-type magnetic tunnel junction sensors by the pinned layer geometry,” (submitted to Applied Physics Express).

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関